Searches for the Violation of Pauli Exclusion Principle at LNGS

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On behalf of the VIP-2 collaboration
Overview

• Experimental *searches* for possible PEP violation,
• Dedicated VIP experiment and result

VIP-2 experiment

• upgrade in VIP-2
• preparation status
Experimental searches for violation of PEP

Search for PEP forbidden states:
- nuclear, atomic.

AMS (Accelerator mass spectroscopy)

Search for PEP forbidden transitions:

**By-product of experiments in Gran Sasso**

BOREXINO
- low energy neutrino spectroscopy,
- $\gamma$Be solar neutrino search

DAMA
- dark matter search

PEP-forbidden nuclear transitions:

$$^{12}C \rightarrow ^{11}\tilde{B} + p$$


Atomic transitions:

$$I \rightarrow I + \gamma$$

“In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers coincide. If an electron exists in an atom for which all of these numbers have definite values, then the state is occupied.”

W. Pauli, Zeitschrift für Physik 31(1925) 765.
Goldhaber & Scharff-Goldhaber experiment

“Are the electrons from nuclear beta decay same as electrons in atoms?”

Goldhaber experiment: shed electrons from $^{14}\text{C}$ source on lead foil. Estimated limit for PEP violation: $\sim 3 \times 10^{-2}$

Fig. 1. Arrangement used in search for photons from beta-rays stopped in lead.

M. Goldhaber and G.S. Goldhaber, Phys. Rev. 73 (1948) 1472
PEP forbidden X-ray transitions

a most intuitive picture:

Normal $2p \rightarrow 1s$ transition

$8.05$ keV for Cu

2p→1s transition violating Pauli Principle

$\sim 7.7$ keV for Cu

anomalous transition X-rays from atomic states
Introduce “new” external electrons by a circulating current to a conducting (Cu) strip, and search for anomalous transition X-rays

\[ \beta^2 / 2 \leq 1.7 \times 10^{-26} \ (> 95\% \ C.L.) \]


Gas-tube detector
15% resolution
@ 8-9 keV

# OF EVENTS (SUM OVER 100 CHAN)

X-RAY ENERGY (keV)

\[ N_X \geq \frac{1}{2} \beta^2 N_{\text{new}} N_{\text{int}} / 10 \]
The parameter “$\beta$”

**Ignatiev & Kuzmin model** creation and destruction operators connect 3 states

- the vacuum state $|0\rangle$
- the single occupancy state $|1\rangle$
- the **non-standard** double-occupancy state $|2\rangle$

through the following relations:

\[
\begin{align*}
  a|0\rangle &= 0 & a^+ |0\rangle &= |1\rangle \\
  a|1\rangle &= |0\rangle & a^+ |1\rangle &= \beta |2\rangle \\
  a|2\rangle &= \beta |1\rangle & a^+ |2\rangle &= 0
\end{align*}
\]

The parameter $\beta$ quantifies the degree of violation in the transition $|1\rangle \rightarrow |2\rangle$. It is very small and for $\beta \rightarrow 0$ we can have the **Fermi-Dirac statistic** again.
The VIP (Violation of the Pauli Principle) experiment

Goal

to improve the limit on the probability of a possible violation of the Pauli exclusion principle for electrons, set in Ramberg-Snow experiment

by means of

- sensitive, large-area, X-ray detectors: Charge Coupled Device (CCD)
- clean, low-background experimental area (LNGS)
Fig. 1. The VIP setup. All elements at the setup are identified in the figure.
Experiment setup - 2

Cu target
Background reduction at LNGS

Why at LNGS?

2 CCD test setup – normalized distributions

- Lab no sh.
- Lab with sh.
- LNGS with sh.

Background reduced by a factor ~ 20
The VIP setup at LNGS
With electrons. Moreover, we used this parametrization for an analysis of several scattering processes on the atoms of the copper lattice.

The probability for the usual antisymmetric one. The parameter $\beta$ is:

$$\beta \sim \frac{\Delta \alpha}{\Delta \theta}$$

The acceptance of the 14 CCD detectors and the probability of X-rays generated in the PEP violating transition generated in the copper target, is not absorbed in the scattering probability.

From preliminary tests, it appears that the X-ray background in the LNGS environment is a factor 10–100 lower than in the Frascati Laboratories. A VIP measurement of two years (one per, under a circulating 40 A current. A new limit for the PEP violation for electrons was found:

$$\beta^2 \frac{I}{2} \lesssim \frac{3 \times 73}{4.9 \times 10^{29}} = 4.5 \times 10^{-28} \text{ at 99.7 CL.}$$


Fig. 2. Energy spectra for the VIP measurements: (a) with current ($I = 40$ A); (b) without current ($I = 0$).
A summary of previous limits and VIP-2 objective

![Graph showing previous limits and VIP-2 objective](image)

- Ramberg-Snow (1990)
- VIP1-LNF (2006)
- S.R. Elliott et al. (2012)
- VIP1-LNGS (2010)
- VIP2

References


The VIP-2 Collaboration


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Compact target with active shielding

Sketch of the VIP2 Setup: 
Cu foil, 2x3 SDD x-ray detectors
Silicon Drift Detectors with timing capability

SDD timing spectrum: SIDDHARTA experiment

VIP CCD energy spectrum

SDD used in SIDDHARTA for kaonic atom X-rays

normal fluorescence X-rays from copper are background from cosmic-ray excited copper atoms

Silicon Drift Detectors with timing capability

SDD timing spectrum: SIDDHARTA experiment

VIP CCD energy spectrum


normal fluorescence X-rays from copper are background,
from cosmic-ray excited copper atoms
→ can be excluded using time information
VIP

![Graph of X-ray energy spectra for VIP](image)

SIDDHARTA

![Graph of X-ray energy spectra for SIDDHARTA](image)

FWHM 340 eV @ 8 keV

FWHM 170 eV @ 8 keV
Region of interest

$I = 40$ A

$X$-ray energy (keV)
The SIDDHARTA setup was installed at the SPring-8 NE collider. It consists of an X-ray detection system, a cryogenic target system, and a kaon detector, as shown in Fig. 1. The whole system was installed at a distance of 78 m between the SDDs and the target central axis. A total active area of 144 cm\(^2\) X-ray detection was installed in the setup used for kaonic atom X-ray events. A total active area of 144 cm\(^2\) X-ray detection was installed with a cryogenic target system, and a kaon detector, as shown in Fig. 1.

The positions at which the SDDs were installed differed from those in the setup used for kaonic atom X-ray events. A larger size of the target, the acceptance of the SDDs was improved by a factor of about 2.6. A total active area of 144 cm\(^2\) X-ray detection. A total active area of 144 cm\(^2\) X-ray detection was installed with a cryogenic target system, and a kaon detector, as shown in Fig. 1.

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The second type (“X-ray tube” data) is data taken with the X-ray tube and degrader, to be used for collection of kaonic atom X-ray events. The production data are correlated with the kaon coincidence (triple coincidence data), produced by radiation from the X-ray tube. Since each SDD has a different gain, the energy scale was determined using the known energy spectrum of the X-ray tube data. The peak positions of the Ti, Cu, and Au peaks with high statistics, mainly in the region of interest, were used to determine the accuracy of the energy scale.

The positions at which the SDDs were installed differed from those in the setup used for kaonic atom X-ray events. A larger size of the target, the acceptance of the SDDs was improved by a factor of about 2.6. A total active area of 144 cm\(^2\) X-ray detection was installed with a cryogenic target system, and a kaon detector, as shown in Fig. 1.

An overview of the experimental setup. The whole system was installed at a distance of 78 m between the SDDs and the target central axis. A total active area of 144 cm\(^2\) X-ray detection was installed with a cryogenic target system, and a kaon detector, as shown in Fig. 1.

Large area silicon-drift detectors (SDDs) having an active area of 1.5 mm, while the one installed above the pipe has a smaller size of 49 mm. Above the upper tube and the Ti and Cu foils. These X-ray tube data were taken periodically (typically every several hours), to be used for the determination of the energy scale of each SDD, and for monitoring the clock pulses delivered by DA Phi1 NE were recorded. The energy data of all the X-ray signals detected by the SDDs were periodically (typically every several hours), to be used for the determination of the energy scale of each SDD, and for monitoring the clock pulses delivered by DA Phi1 NE were recorded. The energy data of all the X-ray signals detected by the SDDs were periodically (typically every several hours), to be used for the determination of the energy scale of each SDD, and for monitoring the clock pulses delivered by DA Phi1 NE were recorded.
Preparation of VIP-2
Beam Test Facility test for scintillators

Dec. 2013, LNF

e^{-} beam
~ 500 MeV/c

calorimeter
scintillators
“finger”

timing performance, efficiency test

artist cut-away view of VIP-2 setup

3 x 2 SDDs

scintillator detectors as active shielding, with readout by SiPMs
Final setup at SMI under test

- Helium compressor
- Vacuum chamber with full detector system
- Data-taking electronics
Detector performances

Time spectrum of one SiPM

- Time resolution of scintillator from BTF measurement

Timing of SDD events

- Time resolution of SDDs from test setup measurement of cosmic rays

Detector efficiencies and time resolutions are confirmed to be capable of achieving the estimated background reduction level in the proposal of VIP2 experiment.
Detector performances

Energy calibration of the SDDs

Residual plot

FWHM @ 6 keV
147 eV

Andreas Pichler:
Application of photon detectors in the experiment to test Pauli Exclusion Principle
## VIP-2 improvement factors

Table 2. List of numerical values of the changes in VIP2 in comparison to the VIP features (given in brackets)

<table>
<thead>
<tr>
<th>Changes in VIP2</th>
<th>value VIP2 (VIP)</th>
<th>expected gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>acceptance</td>
<td>12% (1 %)</td>
<td>12</td>
</tr>
<tr>
<td>increase current</td>
<td>100A (50A)</td>
<td>2</td>
</tr>
<tr>
<td>reduced length</td>
<td>3 cm (8.8 cm)</td>
<td>1/3</td>
</tr>
<tr>
<td>total linear factor</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>energy resolution</td>
<td>170 eV (340 eV)</td>
<td>4</td>
</tr>
<tr>
<td>reduced active area</td>
<td>6 cm² (114 cm²)</td>
<td>20</td>
</tr>
<tr>
<td>better shielding and veto</td>
<td></td>
<td>5-10</td>
</tr>
<tr>
<td>higher SDD efficiency</td>
<td></td>
<td>1/2</td>
</tr>
<tr>
<td>background reduction</td>
<td></td>
<td>200-400</td>
</tr>
<tr>
<td>overall improvement</td>
<td></td>
<td>&gt; 120</td>
</tr>
</tbody>
</table>

outlook for VIP-2

- background and stability measurement at SMI, Vienna;

- transportation of the final setup to LNGS within 2015, for long term data taking.
Summary

- Pauli Exclusion Principle, fundamental yet a postulate, open to experimental test, no quantitative presentation for small amount of violation yet;

- the method of Ramberg & Snow (RS) searches for PEP-forbidden transition of electron;

- VIP experiment with high-precision X-ray spectroscopy, limit with highest sensitivity using RS method;

- VIP-2 will improve sensitivity by two orders of magnitude.

- Possibilities of violation? Serendipity?
Figure 4. Results of PEP violation experiments for electrons.

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References


[13] Di Matteo S., Sperandio L, 2006 VIP Note, IR-04, 26 April 2006; The energy shift has been computed by P. Indelicato, private communication.


Spare
Motivation  
- in the words of W. Pauli  

*PEP lacks a clear, intuitive explanation*

... Already in my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumptions.  

I had always the feeling and I still have it today, that this is a deficiency.  

... *The impression that the shadow of some incompleteness [falls] here on the bright light of success of the new quantum mechanics seems to me unavoidable.*  

W. Pauli, Nobel lecture 1945
How to search for violation? - again

How to search for such states, and how to parameterize, if a tiny amount of violation exists?

ground state for
fermi statistics

n = 2

n = 1

ground state for
PEP-violating statistics:
with “mixed” symmetry

n = 2

n = 1

transitions between different symmetry types are not allowed

??
Calculated “anomalous” transition energies

<table>
<thead>
<tr>
<th>Transitions for Copper</th>
<th>Pauli obeying transitions</th>
<th>Pauli violating transitions</th>
<th>Energy difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard transition</td>
<td>Energy [eV]</td>
<td>Transition probability velocity [1/s]</td>
</tr>
<tr>
<td></td>
<td>Energy [eV]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2p_{1/2} \rightarrow 1s_{1/2} (K_{a2})</td>
<td>8,047.78</td>
<td>7,728.92</td>
<td>2.6372675E+14</td>
</tr>
<tr>
<td>2p_{3/2} \rightarrow 1s_{1/2} (K_{a1})</td>
<td>8,027.83</td>
<td>7,746.73</td>
<td>2.5690970E+14</td>
</tr>
<tr>
<td>3p_{1/2} \rightarrow 1s_{1/2} (K_{b2})</td>
<td>8,905.41</td>
<td>8,529.54</td>
<td>2.7657639E+13</td>
</tr>
<tr>
<td>3p_{3/2} \rightarrow 1s_{1/2} (K_{b1})</td>
<td>8,905.41</td>
<td>8,531.69</td>
<td>2.6737747E+13</td>
</tr>
<tr>
<td>3d_{5/2} \rightarrow 2p_{3/2} (L_{a2})</td>
<td>929.70</td>
<td>822.84</td>
<td>5.9864102E+07</td>
</tr>
<tr>
<td>3d_{5/2} \rightarrow 2p_{3/2} (L_{a1})</td>
<td>929.70</td>
<td>822.83</td>
<td>3.4922759E+08</td>
</tr>
<tr>
<td>3d_{3/2} \rightarrow 2p_{1/2} (L_{b1})</td>
<td>949.84</td>
<td>841.91</td>
<td>3.0154308E+08</td>
</tr>
<tr>
<td>3s_{1/2} \rightarrow 2p_{1/2}</td>
<td>832.10</td>
<td>762.04</td>
<td>3.7036365E+11</td>
</tr>
<tr>
<td>3s_{1/2} \rightarrow 2p_{3/2}</td>
<td>811.70</td>
<td>742.97</td>
<td>7.8424473E+11</td>
</tr>
<tr>
<td>3d_{5/2} \rightarrow 1s (Direct Radiative Recombination)</td>
<td>8,977.14</td>
<td>8,570.82</td>
<td>1.2125697E+06</td>
</tr>
</tbody>
</table>


http://www.lnf.infn.it/sis/preprint/detail.php?id=5330
Interpretation of the experiment results
- capture cross-section (estimated by taking the anomalous electron as muon), cascade processes not clear.

Calculations (Ramberg & Snow)

The number of "new" electrons passing through the Cu conductor:

\[ N_{\text{new}} = \frac{1}{e} \sum I \Delta t \]

The minimum number of scattering process on the atoms of the copper lattice, per electron, is of order:

\[ \frac{D}{\mu} \quad \text{Length of the copper electrode} \]
\[ \frac{D}{\mu} \quad \text{Mean free path of electron in copper} \]

We assume that the capture probability is > 1/10 of the scattering probability.

The X-rays produced in the atomic transitions can be absorbed inside before to reach the detector. Be \( \alpha \) the absorption cross section, the mean absorption length will be:

\[ \lambda = \frac{1}{\sigma \rho} \]

If \( z \) is the copper thickness, the fraction of visible current to the detector will be \( \lambda/z \) and the expected number of X-rays is:

\[ N_X \geq \frac{1}{2} \beta^2 N_{\text{new}} \frac{N_{\text{int}}}{10} = \beta^2 (\sum I \Delta t) \frac{D}{e \mu \rho z \sigma} \]

\[ \int I(t) \, dt = 15.44 \cdot 10^6 \, C \]
\[ D = 0.025 \, m \quad \sigma = 10 \, m^2 \cdot kg^{-1} \]
\[ \mu = 3.9 \cdot 10^{-8} \, m \quad z = 1.5 \cdot 10^{-3} \, m \]
\[ \rho = 8.96 \cdot 10^3 \, kg \cdot m^{-3} \quad e = 1.6 \cdot 10^{-19} \, C \]

\[ N_X \geq \beta^2 \left( 0.90 \cdot 10^{28} \right) \]
\[ \beta^2 / 2 \leq 1.7 \cdot 10^{-26} (> 95\% \, C.L.) \]
Analysis of VIP with RS method:

\[
\Delta N_x \geq \frac{1}{2} \beta^2 N_{new} \frac{N_{int}}{10} f_g = \frac{\beta^2 (\Sigma I \Delta t) D}{e \mu} \frac{1}{20} f_g
\]

\[
\Delta N_x \geq \frac{\beta^2}{2} \left( 4.9 \cdot 10^{29} \right)
\]

\[
\Delta N_x = -21 \pm 73
\]

\[
\frac{\beta^2}{2} \leq \frac{3.73}{4.9 \cdot 10^{29}}
\]

\[
\frac{\beta^2}{2} \leq 4.5 \cdot 10^{-28} \text{ at } 99.7 \text{ C.L.}
\]

\[
\int_I(t) dt = 34.824 \cdot 10^6 C
\]

\[
D = 0.088 m
\]

\[
\mu = 3.9 \cdot 10^{-8} m
\]

\[
\rho = 8.96 \cdot 10^3 kg \cdot m^{-3}
\]

\[
f_g = 0.01
\]
A summary of previous limits

<table>
<thead>
<tr>
<th>Process</th>
<th>Type</th>
<th>Experimental limit</th>
<th>$\frac{1}{2} \beta^2$ limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic transitions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta^- + \text{Pb} \rightarrow \tilde{\text{Pb}}$</td>
<td>Ia</td>
<td>recently created fermions (electrons)</td>
<td>$3 \times 10^{-2}$</td>
</tr>
<tr>
<td>$e_{pp}^- + \text{Ge} \rightarrow \tilde{\text{Ge}}$</td>
<td>Ia</td>
<td></td>
<td>$1.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$e_I^- + \text{Cu} \rightarrow \tilde{\text{Cu}}$</td>
<td>II</td>
<td>distant fermions (electrons)</td>
<td>$1.7 \times 10^{-26}$</td>
</tr>
<tr>
<td>$e_I^- + \text{Cu} \rightarrow \text{Cu}$</td>
<td>II</td>
<td></td>
<td>$4.5 \times 10^{-28}$</td>
</tr>
<tr>
<td>$e_I^- + \text{Cu} \rightarrow \tilde{\text{Cu}}$</td>
<td>II</td>
<td></td>
<td>$6.0 \times 10^{-29}$</td>
</tr>
<tr>
<td>$e_I^- + \text{Pb} \rightarrow \text{Pb}$</td>
<td>II</td>
<td></td>
<td>$1.5 \times 10^{-27}$</td>
</tr>
<tr>
<td>$e_f^- + \text{Pb} \rightarrow \text{Pb}$</td>
<td>Iia</td>
<td></td>
<td>$2.6 \times 10^{-39}$</td>
</tr>
<tr>
<td>$I \rightarrow \tilde{I} + \text{X-ray}$</td>
<td>III</td>
<td>$\tau &gt; 2 \times 10^{27}$ sec</td>
<td>$3 \times 10^{-44}$</td>
</tr>
<tr>
<td>$I \rightarrow \tilde{I} + \text{X-ray}$</td>
<td>III</td>
<td>$\tau &gt; 4.7 \times 10^{30}$ sec</td>
<td>$6.5 \times 10^{-46}$</td>
</tr>
<tr>
<td>Nuclear transitions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{12}\text{C} \rightarrow ^{12}\tilde{\text{C}} + \gamma$</td>
<td>III</td>
<td>$\tau &gt; 6 \times 10^{27}$ y</td>
<td>$1.7 \times 10^{-44}$</td>
</tr>
<tr>
<td>$^{12}\text{C} \rightarrow ^{12}\tilde{\text{C}} + \gamma$</td>
<td>III</td>
<td>$\tau &gt; 4.2 \times 10^{24}$ y</td>
<td>$2.2 \times 10^{-57}$</td>
</tr>
<tr>
<td>$^{12}\text{C} \rightarrow ^{12}\tilde{\text{C}} + \gamma$</td>
<td>III</td>
<td>$\tau &gt; 5.0 \times 10^{31}$ y</td>
<td>$7.4 \times 10^{-60}$</td>
</tr>
<tr>
<td>$^{12}\text{C} \rightarrow ^{11}\tilde{\text{B}} + p$</td>
<td>III</td>
<td>$\tau &gt; 8.9 \times 10^{29}$ y</td>
<td></td>
</tr>
</tbody>
</table>

VIP results


BOREXINO


**Symmetrization Principle**

**a Super-Selection Rule**

“The states of a system containing N identical particles are necessarily either all symmetrical or all anti-symmetrical with respect to permutations of the N particles.”

| The symmetry type of a state of identical particles is absolutely preserved. Hamiltonian for identical particles must be totally symmetric in their coordinates and thus the symmetry type of the states is conserved by the super-selection rule. |

| Transitions are forbidden between states which contain any number of bosons and fermions and at most one particle which is neither a boson nor a fermion and state which have more than one non-Bose or non-Fermi particle, even when the number of particles is not conserved. |

| Hamiltonian forbids transitions between states of many identical particles in different representation of the permutation group. - Greenberg 1989 |